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Energy input, carbon intensity and cost for ethanol produced from farmed seaweed

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ABSTRACT

Macroalgae, commonly known as seaweed, has received significant interest as a potential source of ethanol because of its fast growth, significant sugar content and successful lab-scale conversion to ethanol. Issues such as energy input in seaweed conversion, lifecycle emissions, global production potential and cost have received limited attention. To address this gap, a well-to-tank model of ethanol production from brown seaweed is developed and applied to the case of ethanol production from *Saccharina latissima* in British Columbia, Canada. Animal feed is proposed as a co-product and co-product credits are estimated. In the case considered, seaweed ethanol is found to have an energy return on invested (EROI) of 1.7 and a carbon intensity (CI) of 10.8 $gCO_2e\ MJ^{-1}$. Ethanol production from conventionally farmed seaweed could cost less than conventional ethanol and be produced on a scale comparable to 1% of global gasoline production. A drying system is required in regions such as British Columbia that require seasonal seaweed storage due to a limited harvest season. The results are significantly influenced by variations in animal feed processing energy, co-product credit value, seaweed composition, the value of seaweed animal feed and the cost of seaweed farming. We find EROI ranges from 0.64 to 26.7, CI from 33 to −41 $gCO_2e\ MJ^{-1}$ and ethanol production is not financially viable without animal feed production in some scenarios.

Contents

Abbreviations: BC, British Columbia; CAD, Canadian dollars; CI, carbon intensity; COP, coefficient of performance; EROI, energy return on energy invested; gCO_2e, GHG emission in grams of carbon dioxide equivalent; GHG, greenhouse gas; GWP, global warming potential

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1. Introduction

Ethanol is a proven transportation biofuel that can reduce GHG emissions with minimal infrastructure change, but its expanded use is limited by current ethanol sources. Corn ethanol production can compete for limited arable land and water resource, driving the "food *vs.* fuel" debate [1], and it requires a significant amount of energy for conversion and fertiliser. Expanding sugarcane ethanol production can contribute to deforestation and wetland destruction [2], and sugarcane grows only in specific climates. Cellulosic biomass has been proposed as feedstock to expanded ethanol production and significant advances have been made in making it a commercial reality [3,4]; however, it is fundamentally difficult to convert cellulosic biomass to ethanol due to the presence of lignin.

Macroalgae or seaweed has generated significant interest as an ethanol source because of its potential to overcome these disadvantages and its promise as a biomass source. Seaweeds lack lignin [5], they have high productivity per unit area [5] and they are currently farmed at large scale [6,7] without the use of fresh water or arable land.

As an ethanol feedstock, seaweed also presents several unique challenges. Seaweed has high water content (75–90%) and high ash content (22–37%) [8] which can result in high costs for drying, transportation and processing. Furthermore, seaweed experiences significant monthly fluctuations in fermentable content [9]. As a result of these fluctuations, brown seaweeds like *Laminaria japonica* and *Saccharina latissima* are only harvested during a one to two month period [10,11]. Because ethanol plants require a year round supply of feedstock to achieve acceptable production costs, compensation mechanisms used in corn and sugarcane ethanol production, like feedstock storage or planting species that mature at different rates, may be required for seaweed ethanol. Although seaweed ethanol has received significant attention in the literature, the effects of these challenges on the overall ethanol production system have not been fully addressed.

The objective of this study is (1) provide a complete model of seaweed ethanol production, (2) estimate seaweed ethanol's well-to-tank energy input and carbon intensity, (3) estimate seaweed ethanol production potential using established seaweed farming methods and (4) perform a financial analysis.

Seaweed biomass can be generated from three sources: natural stocks; near shore farming and offshore farming. Natural stocks provide only 6% of global seaweed harvest and offshore farming is still only experimental, leaving near shore as the dominant form of seaweed production. Near shore farming is labor intensive, and the bulk of farming is done in areas where labor cost is low [8]. The brown seaweed, *Saccharina japonica*, is the most farmed seaweed by mass, accounting for 33% of global near shore farming [6].

Apart from water and ash, all brown seaweeds contain five saccharides (*i.e.* alginate, laminarin, mannitol, cellulose and fucans) as well as proteins and small quantities of lipids [12], as shown in Table 1.

Of these five saccharides, laminarin and mannitol are considered easily fermentable [13], and recent work has shown that alginate fermentation is possible with genetically modified fermenting organisms [5,14]. Several components can be extracted as co-products and sold [6] including, pigment proteins, cellulose, fucans and phenolic compounds from the metabolites, and the whole seaweed mass can be anaerobically digested into methane [15], converted into fertilizer, or made into animal feed. Seaweed fertilizer can act as biostimulant [8], and seaweed ash

Table 1
Components of brown seaweed.

Component[a]	Composition[b]	Index[c]
Alginate	23	1
Laminarin	14	2
Mannitol	12	3
Proteins	12	4
Cellulose	6	5
Fucans	5	6
Lipids	2	7
Ash	24	8
Moisture	88	–

[a] Main components of all brown seaweeds [12].
[b] Typical composition for the Laminaria species [23]. Moisture content is given in wet basis, and the remaining component values are given in percentage of total seaweed solids.
[c] Summation index for Eq. (1).

Nomenclature

Symbols

C_{CAP}	ethanol plant capital cost ($)
C_{DD}	drying and delivery cost ($ t^{-1})
$C_{DD^{Max}}$	maximum drying and delivery cost ($ t^{-1})
C_F	plant gate feedstock cost ($ t^{-1})
C_{FM}	seaweed farming cost ($ t^{-1})
$C_{F^{Annual}}$	total annual cost of feedstock ($ t^{-1})
$C_{F^{Max}}$	maximum cost of feedstock ($ t^{-1})
CI	carbon intensity (gCO_2e MJ^{-1})
C_{OP}	ethanol plant operating cost (less feedstock) ($ $year^{-1}$)
E'	specific energy input (MJ MJ^{-1})
EROI	energy return on energy invested
$K_{M'}$	emissions co-product credit (gCO_2e MJ^{-1})
$K_{N'}$	energy co-product credit (MJ MJ^{-1})
L_{CL}	coastline length for baseline region (km)
$L_{CL,X}$	coastline length for region of interest (km)
M_f	moisture content of fresh seaweed
P	seaweed production in baseline region (t $year^{-1}$)
P_{cap}	ethanol plant production capacity (L $year^{-1}$)
R_C	ethanol yield from seaweed solids (kg kg^{-1})
V	ethanol and co-product revenue ($ $year^{-1}$)
Y_X	near shore ethanol production for region of interest (L $year^{-1}$)
f_i	mass fraction for seaweed component *i*
i_{ROR}	target rate of return
t_{OL}	ethanol plant operating life (year)

Greek

η_i	conversion efficiency for seaweed component *i*
ρ_{EtOH}	ethanol density
Ψ_i	ideal ethanol yield for seaweed component *i*

Superscripts

$'$	specific quantity, *i.e.* quantity per MJ of ethanol higher heating value delivered to vehicle fuel tank

contains high amounts of beneficial minerals and trace elements [16,17] which may increase its value as animal feed.

Feed production is simpler than extraction or digestion, requiring only dewatering and or drying of whole seaweed. Animal feed, is the dominant co-product in the corn ethanol industry, and replacing conventional animal feed with corn co-product animal feed results in a significant reduction of both greenhouse gas (GHG) emissions and energy use in the livestock industry. This reduction is accounted to ethanol producers with co-product credits [18].

Bruton et al. [8] notes that mechanical dewatering could be used to stabilize seaweed and reduce the cost of downstream transport and drying; however, dewatering may result in a significant loss of fermentable content. Mannitol and laminarin form a significant fraction of fermentable content in many brown seaweeds, and because both mannitol and branched forms of laminarin are water soluble [13], these components may be lost during dewatering. Even rinsing seaweed with fresh water or exposure to rain may reduce mannitol content [9].

Conversion of seaweed to ethanol has been achieved at lab scale. Using alginate as the sole carbon source, Takeda et al. [5] produced ethanol to a concentration of 13.0 g L^{-1} over three days using a modified strain of *Sphingomonas* sp. Horn [13] produced 0.38 g ethanol per gram of mannitol in an oxygen limited environment using natural *Zymobacter palmae*, however, *Z. palmae* was unable to ferment mannitol under anaerobic conditions. Wargacki et al. [14] produced ethanol from a combination of alginate, laminarin, and mannitol using a modified strain of *Escherichia coli*. Fermenting a sample of *S. japonica* (kombu) produced an ethanol concentration of 4.7% by volume and a yield of 0.281 g of ethanol per gram of dry macroalgae.

The economics of seaweed ethanol production have been examined by Roesijadi et al. who estimated that a feedstock price of 28 $/dry tonne is required for economic ethanol production without considering revenue from co-products.

Two studies of bio-ethanol production from seaweed were reviewed by Roesijadi et al. [6]. In the first study, Aizawa et al. [19] examined ethanol production from seaweed farmed in both coastal and offshore zones and estimated resource consumption for cultivation and production. The overall energy balance was considered similar to that of corn ethanol. In the second study, Peter et al. [20] examined seaweed farming with juvenile seaweed cultured at a fish hatchery and then transferred to ocean farm structures for final grow out. Pumping in the culturing stage, boat fuel for maintenance of ocean structures and ethanol distillation were identified as the largest energy consumers, but no numerical results were given. Roesijadi et al. concluded that lifecycle analyses for seaweed biofuel are scarce in the literature, and that additional assessment is necessary to provide an adequate comparison between seaweed biofuels and conventional biofuels.

Table 2
Comparison of corn distiller's grains to seaweed animal feed.

	Corn distiller's grains with solubles [25]	Seaweed distillation residue[a] (non-ash components) (%)	Seaweed distillation residue[a] (whole product) (%)
Ash	5.8 [26]	0	56
Protein	25–32	36	16
Fiber	40–44	32[b]	14[b]
Fat	8–10	3[c]	1.2[c]

[a] Unfermented components of *Saccharina latissima* from Black [9] September 1947 inlet sample.
[b] Cellulose content for *Saccharina latissima* from Black [40] September 1946 inlet sample.
[c] Assuming a 0.5% lipid content for unprocessed seaweed [45].

2. Materials and methods

In this paper, a general well-to-tank model is presented for the production of ethanol from farmed seaweed, accompanied by a case study and a sensitivity analysis. The model is comprised of three components, as described in Section 3: energy and emissions, financial analysis, and production potential. The model calculates four performance metrics: *Energy Return on energy Invested* (EROI), *Carbon Intensity* (CI), near shore production capacity and maximum feedstock cost. For a given energy carrier production system, EROI is defined as the total useful energy of the

Table 3
Sensitivity analysis.

Varied input parameters	Reference scenario	Min–Max	Units	Source
Co-product energy[a]				
Wet feed mass fraction	0	0–1	–	[17]
Modified feed mass fraction	0.32	–	–	[17]
Dry feed mass fraction	0.67	0–1	–	[17]
Co-product credits[b]				
Animal feed energy credit	3.27	0–5.06	MJ L^{-1}	[17]
Animal feed emissions credit	19.9	0–28.3	$gCO_2e\ L^{-1}$	[17]
Mineral supplement energy credit	0	0–5.06	MJ L^{-1}	[17]
Mineral supplement emissions credit	0	0–28.3	$gCO_2e\ L^{-1}$	[17]
High CI[b]				
Ethanol plant electricity CI	5.6	5.6–244[c]	$gCO_2e\ MJ^{-1}$	[35]
Distillation fuel CI	51	51–97.3[d]	$gCO_2e\ MJ^{-1}$	[34]
Transport[b]				
d_1	1.5	1.5–0.6[e,f]	km	Fig. 6
d_2	200	68–200[f]	km	Fig. 6
d_3	720	0–720[f]	km	Fig. 6
d_4	620	0–620[f]	km	Fig. 6
d_5	25	12.5–25[f]	km	Fig. 6
Drying electricity CI	5.6	5.6–275[g]	$gCO_2e\ MJ^{-1}$	[35]
Drying system COP	30	5.4–30[h]	–	[33]
Ethanol production energy	4.91	4.91–9.82	MJ L^{-1}	[17,36]
Seaweed production rate	18.5	15–22	kg m^{-1} $year^{-1}$	[10]
Sporeling tank power	300	50–300	W	[10]
Conversion efficiency	0.9	0.7–0.94	–	[13,21]
Seaweed feed price	1250	0–1900	\$ t^{-1}	[37,32]

[a] The extreme cases for co-product energy are of 100% wet feed (minimum co-product energy) and 100% dry feed (maximum co-product energy).
[b] Input parameters for co-product credits, high CI and transport are varied simultaneously in the groups indicated.
[c] BC grid electricity (primarily hydro) or Alberta grid electricity (primarily coal).
[d] Natural gas or coal as distillation fuel.
[e] For the wet transport scenario, fresh seaweed is transported 0.6 km by skiff to the barge operating along d_2.
[f] Distance for the minimum transport scenario shown on the left, distances for the wet transport scenario shown on the right.
[g] The solar thermal system is assumed to be powered by renewable electricity similar in CI to BC grid electricity and by a diesel generator (34% efficient, 93.3 $gCO_2e\ MJ^{-1}$ input fuel).
[h] COP lower bound is for the a heat pump based system with thermal storage described by Xie et al. [30], and the upper bound is an approximation for simple seaweed drying systems using only an air circulation fan.

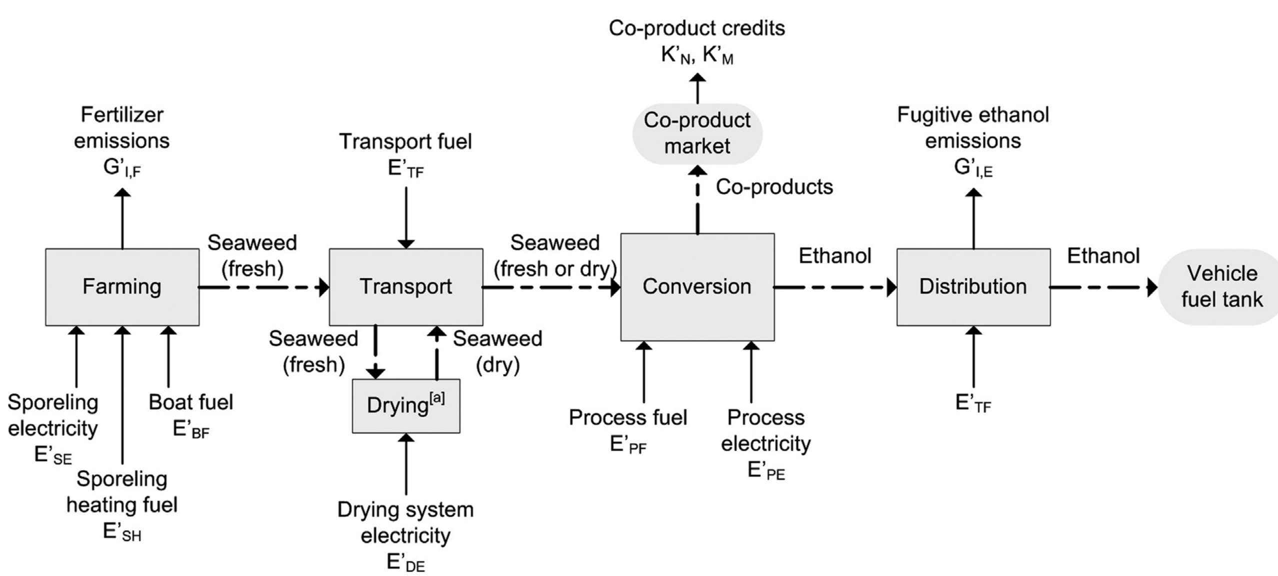


Fig. 1. Energy inputs, emissions and mass flow for seaweed ethanol production. [a] Depending on the need for storage in the region where seaweed is farmed, seaweed may be delivered fresh for immediate conversion to ethanol or dried and stored at the conversion site for later conversion.

produced carrier divided by the total energy input required for carrier production. Similarly, for any energy carrier, CI is defined as the total GHG emission during carrier production divided by the total energy input required to support production. The case study, described in Section 4, applies the model to ethanol production from *S. latissima* in BC. The case study includes a sensitivity analysis, described in Section 4.4, which explores the effects of variations in key input parameters on EROI, CI and maximum

feedstock cost. Data for the case study is drawn from a number of sources which are presented in Section 4 (Tables 1–3) and in Appendix A of the Supplementary material.

3. General model for seaweed ethanol production

The model is divided into three components: energy and emissions, financial analysis, and production potential. The energy and emissions component calculates energy inputs, GHG emissions and co-product credits for seaweed ethanol and co-product production. Inputs, emissions and credits are used to calculate EROI and CI. The financial analysis component examines the cost of seaweed ethanol production by calculating the maximum price that an ethanol conversion facility can pay for seaweed feedstock while remaining profitable. This value is defined as *maximum feedstock cost*. The production component calculates the ethanol production potential of a given coastal region, or *near shore production*, based on seaweed faming in established seaweed farming regions. These three components are discussed in the sections below along with the calculations.

As ethanol has only been produced from seaweed at lab scale, commercial scale ethanol and co-product production are modeled after the dry grind corn ethanol process under three key assumptions: (1) large scale seaweed ethanol processing is similar in cost and energy use to dry grind corn ethanol processing; (2) seaweed ethanol co-product credits and co-product processing energy are similar to those for corn ethanol co-products; and (3) co-product animal feed is equal in value to whole seaweed sold as animal feed. These assumptions are examined in the sensitivity analysis (Section 4.4). In addition, the similarity between seaweed ethanol production and dry grind corn ethanol production is discussed in Section 3.1.4.

3.1. Energy and emissions

The energy and emissions component of the model contains five stages as shown in Fig. 1: *farming* of seaweed; *transport* of seaweed from farm or drying facility to the conversion facility; *drying* of seaweed; *conversion* of seaweed to ethanol; and *distribution* of ethanol to fuel stations for final use. Mass flow is shown with dashed arrows, and energy inputs and indirect emissions are shown with solid arrows. Prime notation indicates a *specific quantity*, *i.e.*, quantity per unit of ethanol energy (HHV) delivered to vehicle fuel tank. Direct emissions for all energy inputs are omitted from the figure for clarity.

The calculation of energy inputs for each stage is described below followed by a treatment of GHG emission and of co-product credits.

3.1.1. Energy for farming

Farming of brown seaweed is comprised of four operations: collection of mature seaweed fronds before spores are released; induced spore release in a land-based seawater tanks; culture of the spores into young seaweed called *sporelings* and; planting of sporelings on ocean-based farm structures for growth into mature seaweed. As shown in Fig. 1, electricity, heating fuel and boat fuel are required to support these operations. Sporeling electricity, $E_{SE'}$, is the electricity input for cooling, lighting and water circulation during sporeling cultivation. Sporeling heating, $E_{SH'}$, is the fuel input (*e.g.* natural gas, coal) needed to maintain appropriate water temperature as the sporelings mature, as required. Boat fuel, $E_{BF'}$, is the fuel consumed while collecting seaweed spores, installing mature sporelings on farm structures, applying fertilizer as the sporelings mature and performing other seaweed cultivation operations as required.

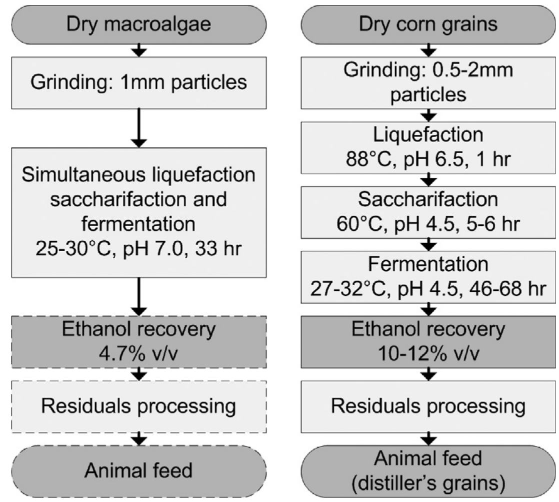


Fig. 2. Comparison of macroalgae conversion [14,22] and dry grind corn ethanol conversion [21]. Additionally modeled steps for macroalgae conversion are shown with dashed borders.

In the model, sporeling electricity use and sporeling heating are calculated from the total electricity and heat input needed per batch of sporelings, the seaweed yield of mature seaweed per batch of sporelings, and a seaweed-to-ethanol conversion factor, called *ethanol yield*, discussed in the "conversion" section below. Boat fuel is calculated using fuel use per unit of seaweed produced and ethanol yield.

3.1.2. Energy for drying

For efficient use of process equipment, ethanol plants require a year round supply of feedstock. In tropical regions, seaweed crops can be produced every 35–45 days [16], potentially enabling a year round feedstock supply, as is the case for sugarcane ethanol. However, regions like China and BC can only produce one brown seaweed crop per year that is harvested during a single 1–2 month period and begins to degrade within a few days of harvest [8,10,11]. For these regions, seaweed must be suitably stored to provide feedstock for year round ethanol production. This is similar to the storage of corn for year round corn ethanol production. Due to the short shelf life of fresh seaweed, some storage may be needed even in regions that can produce fresh feedstock year round. In these regions, logistical issues (*e.g.* equipment failure, disease, storms) are likely to occasionally interrupt the supply of fresh feedstock. Stored seaweed could be used as backup feedstock supply. Like corn, seaweed is typically dried for storage. For long term storage, the moisture content of fresh seaweed must be reduced from between 75% and 90% [8] to less than 22% [10].

Renewable drying systems (*e.g.* solar thermal) typically require electrical energy to operate ancillary components (*e.g.* pumps, fans). To include renewable drying systems in the model, drying energy is characterized by the ratio of drying heat output to electricity input called *coefficient of performance* (COP). Referring to Fig. 1, drying system electricity, $E_{DE'}$, is calculated from required water removal, heat requirement per unit water removed and drying system COP. $E_{DE'}$ is normalized to a specific quantity using ethanol yield.

3.1.3. Energy for transport and distribution

Transport of seaweed and distribution of ethanol requires an array of vehicles (*e.g.* boats, barges, trains, trucks) determined by

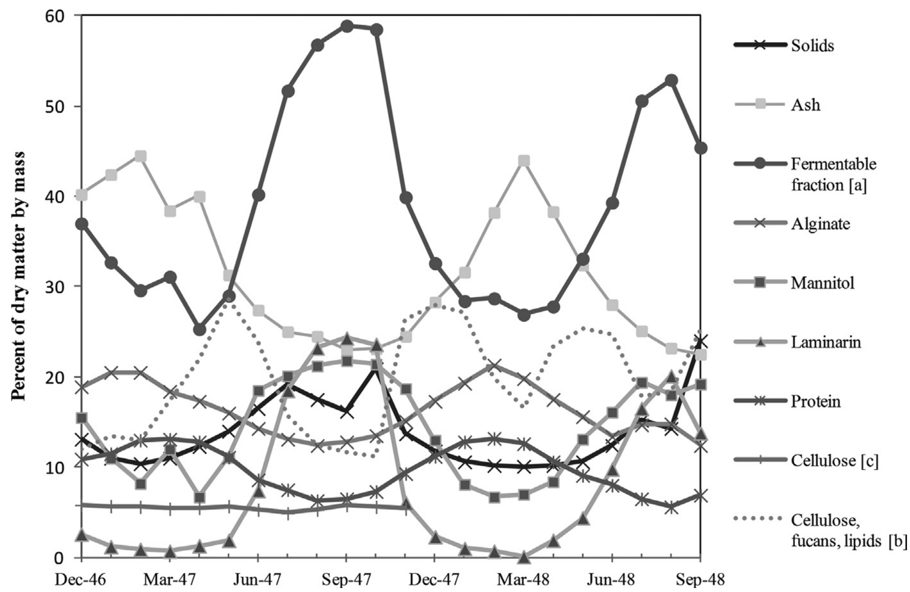


Fig. 3. *Saccharina latissima* composition. Monthly samples of *Saccharina latissima* were taken by Black [9] from natural kelp beds in an inlet and near the open sea. Only data from the inlet location is shown. [a] Fermentable fraction is the sum of alginate, laminarin and mannitol content. [b] The fraction unaccounted for by Black [9] is assumed to be composed of cellulose, fucans and lipids as per the typical components of brown seaweed identified by Percival [12]. [c] Cellulose content for samples taken in Dec 45 to Nov 46 by Black [40] is shown for comparison.

geography, locally available infrastructure, drying heat resource locations (if required) and ethanol plant locations. If seaweed storage is not required, fresh seaweed is collected from seaweed farms distributed over a large area, consolidated for long distance transport and sent to the conversion facility. If storage is required, fresh seaweed is transported to a drying facility and then dried. Dry seaweed is transported to the conversion facility for storage. Using either wet or dry seaweed, the conversion facility produces anhydrous ethanol that is immediately denatured with a small quantity of gasoline. This denatured ethanol can be transported to specially designed fuel stations for immediate use, or sent to a blending facility, mixed with additional gasoline and distributed with existing gasoline infrastructure as low percentage ethanol blends (*e.g.* E5, E10).

In the model, the total energy required for the transport of fresh seaweed, dry seaweed (if applicable), denatured anhydrous ethanol and ethanol/gasoline blends is given by transport fuel, $E_{TF'}$, as shown in Fig. 1. Transport fuel is calculated from the distance traveled, specific mass carried and fuel consumption rate for each transport mode. Specific mass carried is calculated using ethanol yield, ethanol higher heating value and ethanol mass loss during delivery. The energy used to transport the gasoline mixed with denatured ethanol and the gasoline mixed with ethanol blends is not included in the model.

3.1.4. Energy for conversion

Seaweed ethanol has been produced only on the experimental scale [5,13,14]. However, the conversion experiment by Wargacki [14] suggests that commercial seaweed ethanol conversion would be similar to the established process of dry grind corn ethanol production [21]. The basic operations of the dry grind and Wargacki processes, as shown in Fig. 2, are: grind dry feedstock to a fine meal (grinding); mix meal in water and convert polysaccharides into soluble oligosaccharides or polysaccharides (liquefaction); enzymatic breakdown of polysaccharides into fermentable saccharides (saccharifaction); convert saccharides into ethanol with fermenting organisms (fermentation).

Based on the similarity between these processes, it is assumed in the model that commercial seaweed ethanol production requires the same two energy inputs as the dry grind process: (1) boiler fuel to provide heat for saccharifaction, fermentation and distillation and; (2) electricity input for grinding, pumping and other support operations.

In the Wargacki process, only alginate, laminarin and mannitol are converted into ethanol [14,22] leaving five unfermented components (*i.e.* protein, cellulose, fucans, lipids and ash [12]) that could be used to produce valuable co-products including high value extracts (*e.g.* phenolic compounds), animal feed, fertilizer and methane [6]. Note that cellulose is fermentable [3,4], and fucans may fermentable if suitable fermentation organisms are found or created.

Process fuel, $E_{PF'}$, is calculated using fuel use per unit of ethanol produced, ethanol loss in delivery, fuel use per unit of co-product produced for each type of co-product and the mass of each co-product per unit of ethanol produced. Process electricity, $E_{PE'}$, is calculated in the same way, using electricity use per unit of ethanol produced and electricity use per unit of co-product processed. The specific mass of each co-product is calculated from the mass fractions of each unfermented component and ethanol yield, which is discussed below.

Ethanol yield is defined as the mass of ethanol produced per mass of *seaweed solids* (seaweed at 0% moisture) processed. Yield depends on the mass fraction of fermentable saccharides (Table 1) and the efficiency of the conversion process. This mass fraction shows large variations with time of year and farming location. As shown in Fig. 3, Black [9] found that fermentable content for Scottish *S. latissima* ranged between 25% and 59% of total seaweed solids over a two year period.

Black also found that fermentable content differed by up to 28% between the two locations sampled during the same month. Because ethanol yield is directly dependent on fermentable content, composition variation results in a significant change in ethanol yield. Values for ethanol yield are available in the literature [6,8,23], but these yield values do not account for variation in seaweed composition.

In the model, ethanol yield from seaweed solids, R_C, is calculated from the mass fraction of each seaweed component, f_i, *ideal ethanol yield* from each component, Ψ_i, and conversion efficiency for each component, η_i, using Eq. (1),

$$R_C = \sum_i \eta_i f_i \psi_i \tag{1}$$

The subscript, i, in Eq. (1) refers to the five saccharides of brown seaweed, shown in Table 1. Calculation of ideal ethanol yield for mannitol, laminarin and alginate is detailed in Appendix B of the Supplementary material.

3.1.5. GHG emissions

In the model, GHG emissions include direct emissions for the seven energy inputs shown in Fig. 1: transport fuel, sporeling electricity, sporeling heating fuel, boat fuel, drying system electricity, process fuel and process electricity. For transport fuel, direct emissions are calculated using total distance traveled, mass transported, fuel consumed (per t-km) and CI. Direct emissions for the remaining six energy inputs shown in Fig. 1 are based on the energy inputs describe above and the CI of the fuels and electricity used.

The model also calculates indirect emissions for ethanol vapor loss and fertilizer application. Fugitive ethanol emissions, $G_{I,F}$, are calculated using the mass of vapor lost in distribution and the *global warming potential* (GWP) of ethanol vapor. Fertilizer emissions, $G_{I,E'}$, are based on mass of fertilizer applied.

3.1.6. Co-product credits

Co-product credits account for reductions in energy use or emissions caused by co-product use. For corn ethanol production, these credits are typically calculated using the displacement method [18]. In this method, co-products are assumed to displace similar conventional products. The difference between energy consumed in producing co-products and energy consumed in producing conventional products is the co-product credit for energy. Similarly, the difference between emissions from co-product production and emissions from conventional product production is the co-product credit for emissions.

Co-product credits are included in the model as negative energy inputs or negative GHG emissions. Co-product credits for energy, $K_{N'}$ and for emissions, $K_{M'}$, are calculated using the total mass of each co-product produced and credit per unit of co-product.

3.1.7. EROI and CI

EROI is calculated using the specific energy inputs, $E_{i'}$ and co-product credits for energy, $K_{N'}$, for the five stages of seaweed ethanol production discussed above and shown in Fig. 1. Methods for calculation of these inputs and credits are provided in Appendix C of the Supplementary material. EROI is calculated using Eq. (2).

$$\text{EROI} = \frac{1}{\sum_i E_i' - K_N'} \tag{2}$$

Similarly, CI is calculated with Eq. (3) using the direct emissions, $G_{i'}$, indirect emissions, $G_{I,i'}$, and co-product credits for emissions, $K_{M'}$, discussed above and shown in Fig. 1. Calculation of these emissions and credits is provided in Appendix C of the Supplementary material.

$$\text{CI} = \sum_i G_i' + \sum_i G_{I,i}' - K_M' \tag{3}$$

CI is measured in *grams of carbon dioxide equivalent* (gCO_2e) per MJ of ethanol higher heating value.

3.2. Financial analysis

The cost per tonne of dry feedstock at the gates of the ethanol production facility, C_F, is determined by the cost of farming, C_{FM}, and the combined cost of drying and delivery, C_{DD}, as shown in Eq. (4).

$$C_F = C_{FM} + C_{DD} \tag{4}$$

Seaweed farming, drying and delivery costs vary significantly with seaweed species, farming method, drying method and region of farming and cannot be readily captured in a general model. Instead, a *maximum cost of feedstock*, C_F^{Max}, is determined, which is the maximum price that the conversion facility can pay per tonne of dry (22% moisture [10]) feedstock delivered to the plant gates, while achieving its target rate of return.

To calculate C_F^{Max}, the total annual cost of feedstock, C_F^{Annual}, to achieve the target rate of return, i_{ROR}, is first determined, using Eq. (5).

$$C_F^{Annual} = V - C_{OP} - C_{CAP}\left(\frac{i_{ROR}(1+i_{ROR})^{t_{OL}}}{(1+i_{ROR})^{t_{OL}} - 1}\right) \tag{5}$$

where V is annual ethanol and co-product revenue, C_{OP} is annual operating cost (less feedstock cost), C_{CAP} is capital cost and, t_{OL} is ethanol plant operating life. C_F^{Max} is then determined from C_F^{Annual}, ethanol yield, R_C, and ethanol plant production capacity, P_{CAP}, using Eq. (6).

$$C_F^{Max} = \frac{C_F^{Annual} \cdot R_C}{P_{cap} \rho_{EtOH}} \tag{6}$$

If the cost of seaweed farming is known, a maximum drying and delivery cost is determined. This is the drying and transport cost for one tonne of seaweed solids delivered to the conversion facility gates. Maximum drying and delivery cost, C_{DD}^{Max}, is calculated from C_F^{Max}, and the cost of seaweed farming, C_{FM}, using Eq. (7).

$$C_{DD}^{Max} = C_F^{Max} - C_{FM}. \tag{7}$$

3.3. Production potential

The model includes a tool for estimating the seaweed ethanol yield from near shore seaweed farming in a given coastal region. Installing near shore seaweed farming capacity and ethanol conversion systems is a complex issue. Farm sites require viable levels of ocean current and nutrient concentration. Near shore farm sites require suitable sites for anchoring, and the overall ethanol system competes with shipping and recreation for ocean space [10].

In the model, seaweed farming is estimated by assuming that all coastline in the region of interest produces seaweed at the same average rate (*i.e.* tonnes of seaweed per km of coastline per year) as a baseline region of coastline with established near shore seaweed farms. Near shore ethanol production for the region of interest, Y_X, is calculated using coastline length for a baseline region, L_{CL}, the annual seaweed production in the baseline region, P, and ethanol yield as shown in Eq. (8).

$$Y_X \cong \frac{P(1-M_f)R_C}{L_{CL}\rho_{EtOH}} L_{CL,X} \tag{8}$$

$L_{CL,X}$ is the length of coastline for region of interest and M_f is the moisture content of fresh seaweed.

4. Case study

The general model described above is applied to the case of near shore seaweed farming and ethanol production in BC,

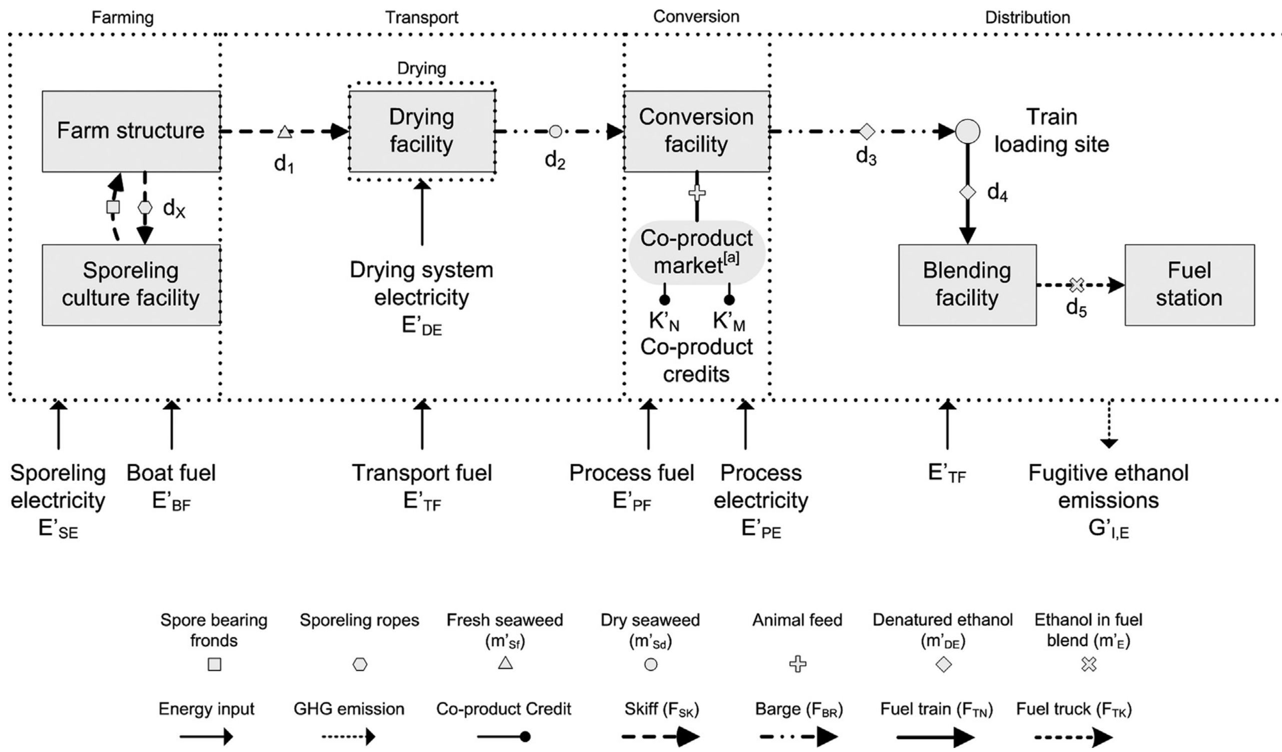


Fig. 4. Case study of ethanol production in BC. [a] Energy input to transport animal feed to the co-product market is not calculated as an input as it is already deducted from the co-product credit data.

Canada. Additional calculations needed to apply the general model are described below. EROI, CI, near shore ethanol production, and maximum feedstock cost for BC are calculated for a set of input parameter values defined as the *reference scenario*. EROI, CI, and maximum feedstock cost are then examined in a sensitivity analysis where key input parameters are varied relative to their reference scenario values.

4.1. Energy and emissions

The structure of the case study model is shown in Fig. 4. Energy inputs, emissions, and co-product credits are divided into five groups (*i.e.* farming, transport, drying, conversion and distribution) as in the general model (Fig. 1) with group boundaries shown in as dashed lines. Facilities are shown with solid boxes, mass transport operations are shown with an arrow and icon combination and legend and direct emissions from each energy input are omitted for clarity. Energy inputs, GHG emissions and co-product credits for the case study are calculated using the mass flows, transport modes and facilities shown in the figure. Transportation distances, d_i, are taken from the transport scenarios shown in Fig. 6 and numerical values are shown in Appendix A of the Supplementary material.

4.1.1. Energy in farming

Sporeling electricity, $E_{SE'}$, boat fuel, $E_{BF'}$, seaweed harvest season and seaweed composition are modeled based on the process used by Cross [11] for *S. latissima* cultivation in BC. As shown in Fig. 4, this process requires a floating farm structure (Fig. 5), a sporeling culture facility to prepare young seaweeds for the farm structure and a small boat or skiff.

Farming begins in late September with the collection of spore bearing seaweed fronds from the floating farm structure. These are brought to a tank of sterilized seawater at the sporeling culture facility and the fronds are chemically forced to release their spores.

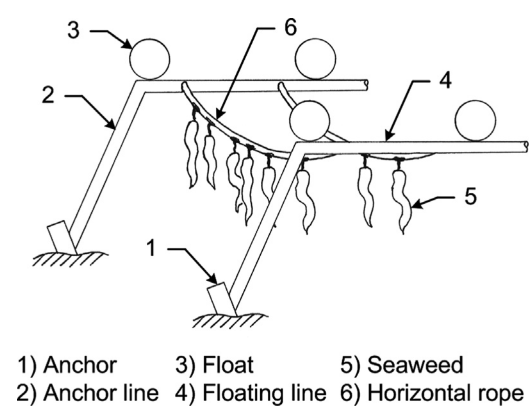


Fig. 5. Horizontal rope farm structure [10].

The spores attach to submerged lengths of twine and generate sporelings. The sterilized seawater provides all of the nutrients needed to produce mature sporelings. The tank is artificially illuminated, electrically heated and its water circulated for 6–8 weeks while the sporelings grow to a length of 1–2 mm. The twine segments are then manually transferred to the ocean farm structure, using a gasoline powered skiff, and installed on floating ropes. The sporelings are left to grow into mature seaweed over the next 7–8 months without additional cultivation. Seaweed growth is negligible overwinter, but increases rapidly in March when light levels increase. Seaweed biomass reaches a maximum at the end of July and declines in the following months. At maximum biomass, a portion of the crop is left to develop spores for producing the next generation of sporelings and the remaining seaweed is harvested manually by collecting the ropes to which the seaweed is attached. Harvest is assumed to occur in July and August, defining the *harvest season*.

Sporeling electricity is calculated from the average power draw of the sporeling tank, the time to produce a batch of sporelings

and seaweed produced per batch. Boat fuel is calculated from the distance traveled by the skiff and total skiff idling time during the collection of mature fronds, installation of seedlings and harvesting of seaweed. Specific sporeling electricity use and boat fuel use are calculated using ethanol yield (Eq. (1)).

4.1.2. Energy in drying

It is assumed that all seaweed is dried before transport to the conversion facility using a solar thermal system. This drying system is powered by electricity from the BC grid. Drying system electricity, $E_{DE'}$, is calculated as in the general model (Appendix C of the Supplementary material.

4.1.3. Energy in transport and distribution

Transport fuel, $E_{TF'}$, is calculated using the transportation and distribution pathway shown in Fig. 4. Fresh seaweed is transported from the farm structure to a nearby drying facility with a small skiff. The seaweed is then dried and barged to the conversion facility for storage and conversion to ethanol. Denatured ethanol (97% by volume [18]) is transported from the conversion facility by barge and train to a blending facility where it is combined with gasoline to produce a 5% by volume ethanol/gasoline blend (E5). The fuel blend is trucked to fuel stations and transferred to vehicle fuel tanks for final use. Transport fuel is calculated from the distance traveled, d_i, mass transported, $m_{i'}$, and fuel consumption, F_i, for each transport mode, as described in the general model (Appendix C of the Supplementary material.

4.1.4. Energy in conversion

Process fuel, $E_{PF'}$, and process electricity, $E_{PE'}$, are the combined fuel and electricity use of ethanol production and co-product production. As discussed earlier, energy use in ethanol production is calculated using data from existing dry grind corn ethanol plants. There are, however, several differences between seaweed ethanol production and corn ethanol production that may affect energy use: (1) A jet cooker is used for liquefaction in corn ethanol conversion, but this may not be needed for seaweed conversion. For example, in alginate extraction, seaweed is soaked in water for several hours to hydrate the seaweed in preparation for chemical treatments [24]; (2) Pumping and mixing energy input may be required as alginate forms viscous gels and fibrous masses in water [24]; (3) Additional corrosion resistance measures or other process changes may also be needed as seaweed has a high natural salt content [17]; (4) processing temperatures are generally lower and pH levels generally more neutral in the Wargacki process. As these differences could not be quantified, the net effect of these differences is assumed to be negligible.

A further difference between these processes is that the experiment conducted by Wargacki resulted in an ethanol concentration of 4.7% by volume whereas a typical corn ethanol plant achieves 10–12% ethanol by volume. Based on this data, the energy required for distillation in the seaweed ethanol process will be more than 200% of that required in the dry grind corn ethanol process. However, as the Wargacki data is based on small-scale experiments, it is assumed in the case study model that future seaweed ethanol fermentation processes will be developed that produce concentrations in the 10–12% range typical of corn ethanol plants.

It is assumed that the unfermented components of seaweed are used exclusively as animal feed because (1) the unfermented components in seaweed are similar in composition to the unfermented components of corn that comprise distiller's grains (Table 2) and (2) seaweed is currently used as animal feed [16] and that it is processed in a similar manner to animal feed produced in the dry grind process.

In the dry grind process, distillation residue is dried to various moisture levels to produce a variety of animal feed products collectively referred to as *distiller's grains*. The three main types of distiller's grains are *wet distiller's grains with solubles*, WDGS, *modified distiller's grains with solubles*, MDGS and *dry distiller's grains with solubles*, DDGS. Raw distillation residue typically contains 65% moisture and is called WDGS when sold as feed, MDGS are dried to 55% moisture and DDGS are dried to 10% moisture [18]. In the case study, it is assumed that seaweed ethanol distillation residue is processed into three steams: *wet feed*, *modified feed* and *dry feed* with the same moisture content as WDGS, MDGS and DDGS, respectively. It is also assumed that these streams are produced in the same proportions as the distiller's grains produced by the dry grind plants surveyed by Bremer et al. [18]. Fuel energy per unit mass of wet feed, modified feed and dry feed processed is assumed equal to fuel energy in the dry grind process for processing WDGS, MDGS and DDGS respectively. Electrical energy for co-product processing is calculated by scaling the total electrical input for distillers grain processing by the ratio of total feed mass processed to total distiller's grain mass processed. The total mass of wet, modified and dry feed processed is assumed equal to the total mass of unfermented components in the seaweed feedstock. The mass of each feed type processed per unit of ethanol produced is calculated using ethanol yield, as described below.

Ethanol yield is calculated from seaweed composition, ideal ethanol yield and conversion efficiency using Eq. (1). Seaweed composition for BC *S. latissima* is approximated by the composition of Scottish *S. latissima* provided by Black [9]. As described above, BC seaweed is harvested during its period of maximum biomass content, therefore, seaweed composition is assumed equal to that of Scottish *S. latissima* for its period of maximum biomass content in September. As shown in Appendix B of the Supplementary material, ideal ethanol yields for alginate, laminarin and mannitol are $0.523\ g\,g^{-1}$, $0.568\ g\,g^{-1}$ and $0.506\ g\,g^{-1}$,respectively. 90% Conversion efficiency is assumed for alginate, laminarin and mannitol in the reference scenario which is similar to the 90–94% efficiency achieved by established conversion processes like corn ethanol [21]. 80% Conversion efficiency, as shown by Wargacki et al. [14], is included in the sensitivity analysis.

4.1.5. GHG emissions

GHG emissions for the case study are calculated in the same way as for the general model, but with the addition of a transport scaling factor and the removal of fertilizer emissions. Direct emissions for all inputs are calculated using emissions factors and the six energy inputs shown in Fig. 4. Transport fuel direct emissions are calculated from the total distance traveled, mass flow carried, fuel consumption rate and fuel carbon intensity of each required vehicle shown in Fig. 4 Fugitive ethanol emissions, $G_{I,E'}$, are calculated from the mass of vapor lost and ethanol vapor GWP. Indirect emissions from fertilizer application are not included as seaweed farming in BC does not typically require fertilizer [11].

4.1.6. Co-product credits

As shown in Table 2, the ash component and non-ash components of seaweed comprise approximately 56% and 44% of total dry mass, respectively. Compared to corn distiller's grains, the non-ash components have similar fiber and protein content. The ash component contains valuable macrominerals and trace elements [16,17] that have value as a mineral supplement.

Co-product credits for energy, $K_{N'}$, and for emissions, $K_{M'}$, are calculated separately for the ash component and for the non-ash components. It is assumed that the ash component replaces animal mineral supplements and that the non-ash components replace

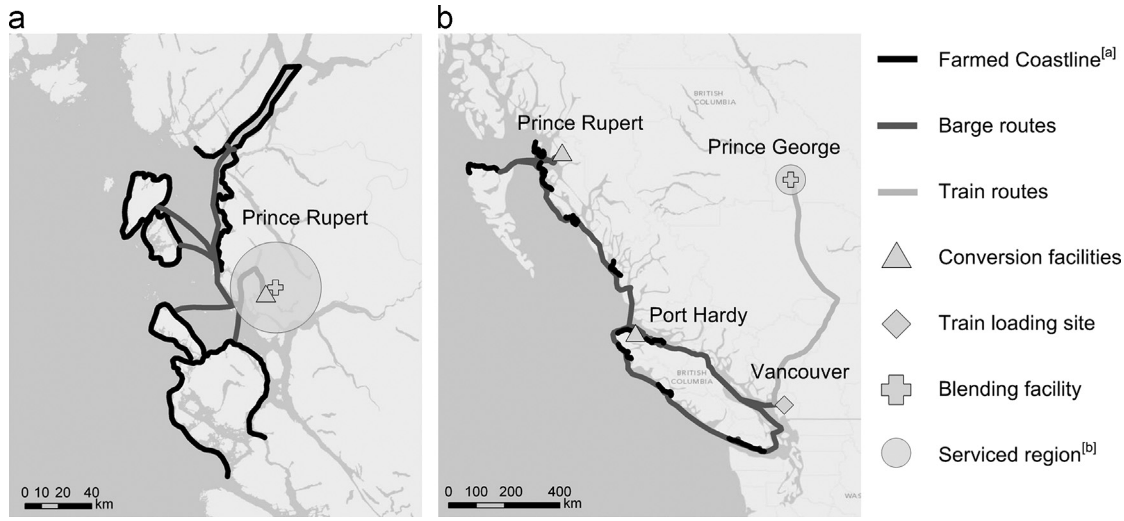


Fig. 6. Transportation distances for the reference, maximum and minimum transport scenarios. The minimum transport scenario is shown in Fig. 6a, and both the reference and maximum transport scenario are shown in Fig 6b. [a] Coastline sections containing sporeling culture facilities, farm structures and drying facilities. [b] Region containing fuel stations serviced by a centrally located E5 blending facility. Vehicles used for transport shown in Fig. 4 and distances are listed in Table 6 of Appendix A (Supplementary material).

animal feed, in the same manner that corn distiller's grains replace animal feed. It is also assumed that energy and emission co-product credits for the non-ash components are similar to those for corn distiller's grains. Credits for the ash component are assumed to be zero as data for displaced mineral supplements is not available.

4.1.7. EROI and CI

EROI and CI are calculated using Eqs. (2) and (3) and the energy inputs, emissions and co-product credits shown in Fig. 4.

4.2. Financial analysis

Capital and operating costs for liquefaction, saccharifaction, fermentation and distillation of seaweed are assumed to be equal to that of dry grind corn ethanol production. Capital and operating costs for seaweed animal feed processing are calculated by scaling the capital and operating costs of dry grind animal feed processing by the mass of seaweed feed processed per unit of ethanol produced. The capital cost of feedstock storage is calculated assuming the cost per unit volume of seaweed storage is equal to that of corn grain storage and that the seaweed ethanol plant includes storage capacity for one year of production. Corn ethanol plants purchase grain in small batches from off-site grain storage companies and have storage capacity for only 8–12 days of operation [21]. However, such offsite storage services for seaweed are not available in BC. Cost data is provided by McAloon et al. [25] and shown in Appendix A of the Supplementary material. Cost data is provided in 1998 USD and converted to 2012 Canadian dollars based on total inflation of 138% over that period [26]. Ethanol revenue is calculated using the wholesale price of gasoline in BC (0.83 $\$\,L^{-1}$ [27]) as an approximation for the price of ethanol. Co-product revenue is calculated using the price of feed grade seaweed (1900 $\$\,t^{-1}$ [28,29]) as an approximation for the price of seaweed co-product animal feed.

For the purposes of calculating maximum feedstock cost and maximum drying and delivery cost, the target rate of return for the reference scenario is 20%.

4.3. Production potential

Near shore production data for British Columbia is not available as British Columbia does not have a commercial seaweed industry. China is the world's largest producer of farmed seaweed and production

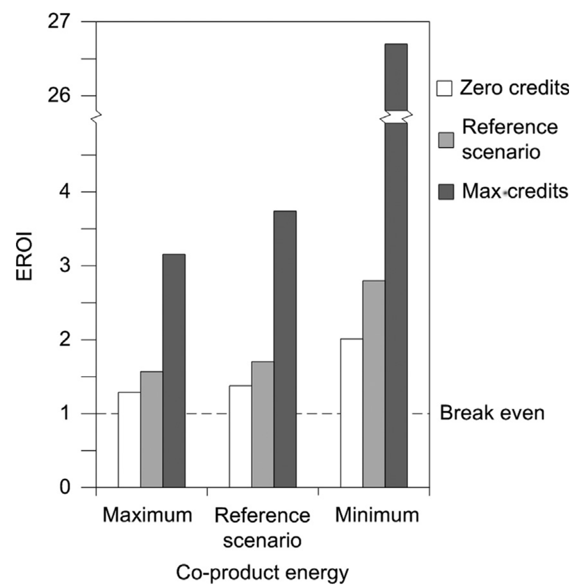


Fig. 7. EROI of seaweed ethanol. EROI varies significantly with the energy input for co-product production and co-product credits for animal feed production.

data for this area is available. Estimates of near shore production for both the BC and the global coastline are estimated using Chinese production data and Eq. (8). The average fermentable content and solids content of the seaweed produced is assumed to be equal to that of the *S. latissima* sampled by Black [9] for September 1947.

4.4. Reference scenario and sensitivity analysis

Input data for the reference scenario is provided in Appendix A of the Supplementary material. Additional relations required to prepare input data for the general model are provided in Appendix D of the Supplementary material. EROI, CI and maximum feedstock cost for the reference scenario are generated for two sets of seaweed composition data from the inlet location: September 1947 and October 1947 (Fig. 3). Results presented below for EROI, CI and maximum feedstock cost are the average of these two sets of results.

The sensitivity analysis was undertaken in two stages. In the first stage, key input parameters were individually varied from their reference scenario values by ±50% to determine effects on

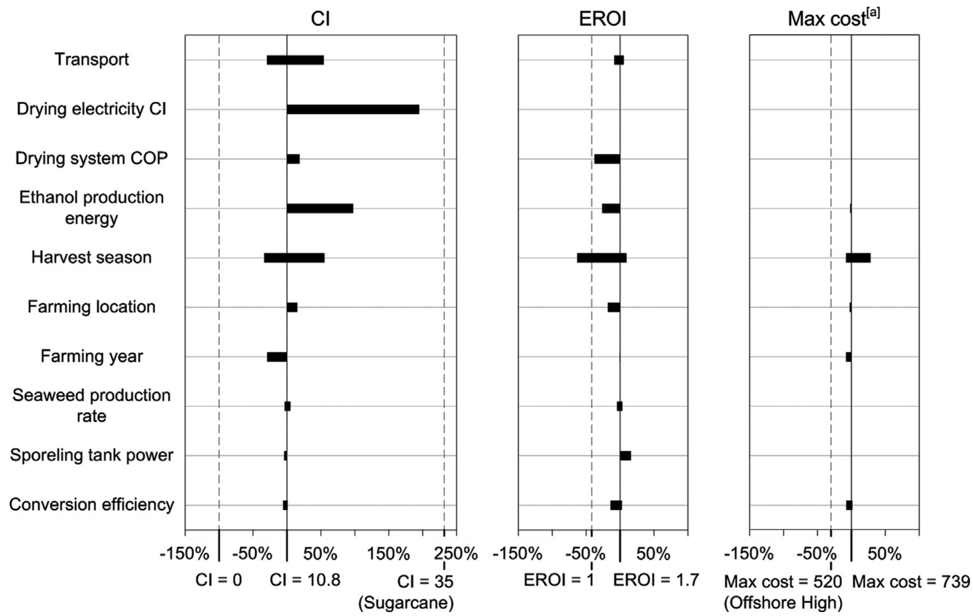


Fig. 8. Sensitivity analysis results. CI, EROI, and maximum allowable cost from the reference scenario are shown with solid vertical lines. Comparison values for sugarcane ethanol CI and offshore seaweed farming cost are taken from Figs. 9 and 11 respectively and shown with dashed vertical lines. [a] Max cost = maximum feedstock cost.

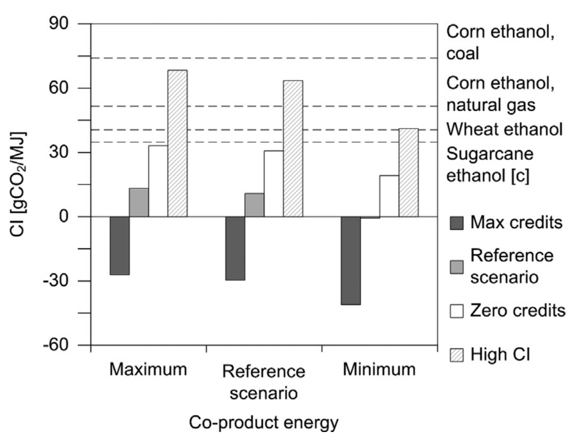


Fig. 9. CI of seaweed ethanol. CI data for corn, wheat and sugarcane ethanol is taken from GHG Genius [41]. [c] Domestic use of sugarcane ethanol is approximated using by replacing transportation emissions for delivery from Brazil to Canada with domestic delivery emissions for Canadian corn ethanol [41].

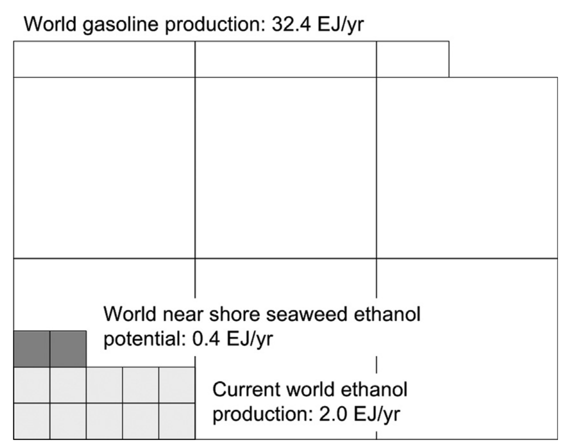


Fig. 10. Global near shore production compared to current world ethanol production [42] and world gasoline production [43].

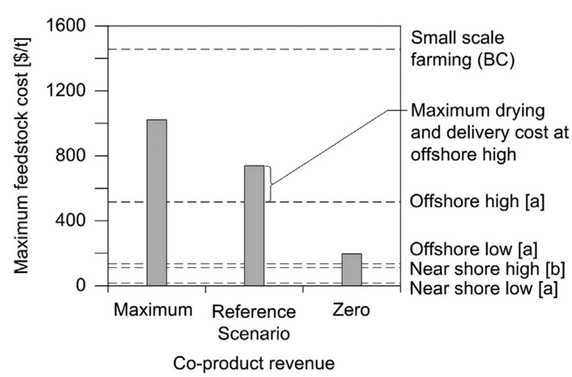


Fig. 11. Maximum feedstock cost. The cost of seaweed farming is shown with dashed lines. [a] Bruton et al. [8] citing Chynoweth [15]. [b] Roesijadi et al. [6]. Farming cost is adjusted for inflation and converted to Canadian dollars [26,44]. Small scale farming data is provided by Druehl [37].

EROI, CI and maximum feedstock cost. Any input parameter that produced less than a $\pm 5\%$ variation in all three performance metrics was not included in the second stage of the sensitivity analysis. In the second stage, probable ranges for all remaining input parameters were identified from the literature as listed in Table 3.

Drying electricity CI ranged from 5.6 $gCO_2e\ MJ^{-1}$ for BC grid electricity to 275 $gCO_2e\ MJ^{-1}$ representing a diesel generator. Drying system COP ranged from 5.4 for a heat pump based system with thermal storage [30] to 30 representing a passive solar system with input only for air circulation fans. The case of conventional seaweed drying fueled by natural gas was also considered using COP = 1 and drying heat CI = 51 $gCO_2e\ MJ^{-1}$ [31]. Conversion efficiency ranged from 70% (below that achieved by the Wargacki experiment) to 94% (the higher end typically achieved by dry grind corn ethanol [21]). Seaweed production rate was set to the range of production rates observed by Cross [11], *i.e.*, 15–22 kg m^{-1} $year^{-1}$. Sporeling tank power ranged from the level given by Cross for his experimental system to a future design with lower power consumption, 300–50 W [11]. Ethanol production energy (*i.e.* boiler fuel use) ranged from 9.82 MJ L^{-1} for distilling ethanol with an initial concentration of 4.7% by volume, as achieved by Wargacki [14], to 4.91 MJ L^{-1} for distilling at 10–12% as typically achieved in corn ethanol production

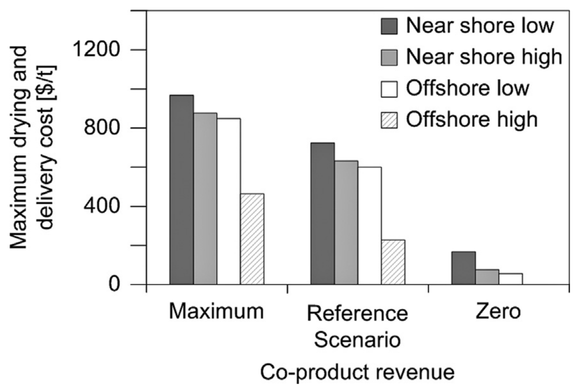


Fig. 12. Maximum drying and delivery cost. The cost of drying and delivery is most affected by revenue from co-product (*i.e.* animal feed) revenue and by the cost of seaweed farming. The cost of seaweed farming exceeds maximum feedstock cost in the case of zero co-product revenue and offshore high farming cost, so there is no allowance left for drying and delivery.

[21]. Seaweed animal feed co-product revenue was varied from zero to 1900$ t^{-1}.

Sensitivities to co-product credits, co-product energy, transportation energy and fuel and electricity CI are examined by varying multiple inputs simultaneously, as shown in Table 3 and as described below. Co-product credits are examined considering: (1) a zero co-product credit scenario in which energy and emissions credits are set to zero for both the ash component and the non-ash components, and (2) a maximum credit scenario where energy and emissions credits are set to the maximum credit values found by Bremer [18]. Fuel and electrical energy use in co-product production were examined considering: (1) a minimum co-product energy scenario based on 100% wet animal feed production (*i.e.* zero boiler fuel use), and (2) a maximum scenario based on 100% dry animal feed production. For transportation energy, minimum and maximum transport scenarios were defined, as shown in Fig. 6. The maximum transport scenario uses the same transport distances as the reference scenario, however, in the maximum transport scenario; seaweed is not dried before transport to the conversion facility.

In the minimum scenario, seaweed is dried near the farm site, as in the reference scenario, but seaweed and ethanol transportation distances are significantly reduced. In the maximum scenario, seaweed and ethanol are transported the same distances as in the reference scenario, but seaweed is transported to the conversion facility without drying. Sensitivity to fuel CI and electrical energy CI was examined considering a high CI scenario in which coal was used for both distillation energy and electricity. The effect of changing the harvest season is investigated for the range of 1947 monthly data for the inlet location provided by Black [9]. The range of values for farming location is based on September 1947 data for the inlet location and the open sea location. The range of values for farming year is based on September 1947 and 1948 inlet location data. Additional detail for ranges and values are given in Appendix A of the Supplementary material.

5. Results

5.1. EROI

For the reference scenario, seaweed ethanol has an EROI of 1.7 (Fig. 7). Seaweed ethanol EROI is strongly affected by co-product credits and production energy (*i.e.* feed mix) (Fig. 7). EROI is affected to a lesser degree by the nine inputs shown in Fig. 8. Using a low power sporeling tank system increases EROI to 2.0. Both drying system COP and harvest season result in an EROI near or below 1. Farming location, ethanol production energy and conversion efficiency each produce an EROI that is greater than 1 but less than 1.5. EROI is 0.35 for the case of conventional drying considering only drying heat.

5.2. CI

For the reference scenario, seaweed ethanol has a CI of 10.8 $gCO_2e\ MJ^{-1}$, as shown in Fig. 9. This is lower than the CI of all conventional ethanol sources shown for comparison. CI is strongly affected by input energy CI, and, to a lesser degree, by co-product credits and production energy (Fig. 9). CI is also affected by nine other inputs shown in Fig. 8. Of particular note, seaweed ethanol CI is significantly affected by drying electricity CI but only minimally affected by transport and ethanol production energy. CI is 128 $gCO_2e\ MJ^{-1}$ for the case of conventional drying considering only drying heat.

5.3. Near shore production

Potential near shore ethanol production for BC is approximately 1.3 billion l per year. For comparison, the mandated minimum ethanol content for all gasoline in BC [32] requires 240 million l per year. Processing this near shore potential would require seven typical ethanol plants with capacities of 200 million l [33].

Potential near shore production for the global coastline is 18.4 billion l per year. This production would require 90 ethanol plants. As shown in Fig. 10, global near shore production potential is an order of magnitude lower than current global ethanol production and two orders of magnitude lower than global gasoline production.

5.4. Maximum feedstock, drying and delivery cost

Maximum feedstock cost for the reference scenario is 739 $ t^{-1} of seaweed solids, as shown in Fig. 11. Large scale seaweed farming costs range from 22 $ t^{-1} of seaweed solids (*i.e.* near shore low) to 520 $ t^{-1} (*i.e.* offshore high) [6,8], also shown in Fig. 10. Therefore, to achieve the target rate of return, total drying and delivery costs range from of 717 to 219 $ t^{-1} (Fig. 12). Note that, at 1460 $ t^{-1}, the current cost of farming at small scale in BC is greater than maximum feedstock cost, preventing profitable ethanol production. Maximum feedstock cost is significantly affected by co-product revenue (Fig. 11), partially affected by seaweed harvest season (Fig. 8) and marginally affected by ethanol production energy, farming location, farming year and conversion efficiency (Fig. 8). Because of the significant effect of co-product revenue, ethanol plant capital cost, ethanol plant operating cost and target rate of return each produced less than a 5% variation in maximum feedstock cost and thus were not included in the second stage of the sensitivity analysis.

6. Discussion

Seaweed ethanol shows significant promise as a low carbon biofuel with high EROI. For the case study, seaweed has a CI lower than all current sources of ethanol, including ethanol produced from corn. If typical corn ethanol co-product credits are applied to the entire mass of seaweed co-product (*i.e.* the ash component and the non-ash component), total emission credits are greater than total well-to-wheel emissions for ethanol production, resulting in ethanol with a significantly negative CI. In the case study, EROI is similar to that of corn ethanol production for the reference scenario. Co-product credits and alternate co-product production scenarios result in EROIs that, in several cases, are more than

double that of corn. In the best case considered (*i.e.* minimum co-product production energy use and maximum co-product energy credits), co-product energy credits are nearly equal to total well-to-wheel energy use in ethanol production resulting in an EROI of 26.7. Even in the worst case considered (*i.e.* zero co-product credits and maximum co-product production energy use), EROI exceeds unity (*i.e.*, EROI = 1.3), and CI is similar to that of sugarcane ethanol. Thus, co-product credits are not necessary for seaweed ethanol to have acceptable EROI and low CI. However, if available, co-product credits enable superior performance, in terms of CI and EROI, relative to other sources of ethanol.

Seaweed has two advantages over other ethanol sources that contribute to the low CI and high EROI of seaweed ethanol: (1) Seaweed can be produced without fertilizer use [34], depending on natural nutrient levels in the region of production. Fertilizer production and use account for over 30% of total emissions in corn ethanol production [18]; (2) Seaweed has a lower total fermentable content than corn (27–59% for seaweed as shown in Fig. 3 *vs.* 72% for corn [21]). As a result, seaweed ethanol production yields higher rates of co-product production per unit of ethanol produced and, thus, leads to greater co-product credits per unit of ethanol produced. Note that this advantage comes with the trade-off of higher feedstock use per unit of ethanol produced.

6.1. Co-product revenue

Animal feed co-product revenue also has significant impacts on process economics. Compared to the case of zero co-product revenue, co-product revenue in the reference and maximum scenarios increases maximum allowable cost by factors of 3.8 and 5.2, respectively. In the reference scenario, the acceptable cost for drying and delivering seaweed is greater than the offshore low farming cost estimate for all cases of large scale seaweed farming shown in Fig. 11 (*i.e.* near shore low to offshore high). These results are not significantly affected by variations in capital or operating costs, as shown in the sensitivity analysis. Thus, the high value of animal feed allows the profitable use of significantly more expensive ethanol plant, which could help fund the development of large scale seaweed conversion systems.

In the case of zero co-product revenue, a drying and delivery allowance equal to the cost of farming is only possible, if farming cost lies between the near shore low and near shore high cost estimates (Fig. 11). Thus, it may be possible to produce profitable ethanol in combination with low value co-products like fertilizer and bio-methane.

The promise of animal feed as a seaweed co-product may, however, be limited by its sodium content. For the case study, the seaweed feed produced has an average ash content of 56% and the seaweed animal feed production rate is 1.21 kg of dry mass per liter of ethanol produced. With seaweed ash containing 12% sodium or more by weight [17] and cattle tolerating feed with a maximum sodium content of 0.1% of total feed dry mass [35], the maximum amount of seaweed feed that can be included in cattle rations or *inclusion rate* is 0.83% of total cattle feed dry mass. Based on this inclusion rate for beef, dairy and swine, the US feed market (a considered by Bremer et al. [18]) could accept seaweed feed from 890 million l of ethanol production per year. This would require 17 million t of fresh *S. latissima* per year, roughly equal to the current total output from global seaweed farming [6]. Processing this volume of seaweed would require 4–5 average size commercial ethanol plants, each with a production capacity of 200 ML year^{-1} [33]. For comparison, Bremer et al. calculated that US beef, dairy and swine have maximum theoretical feed inclusion rates of 45%, 30% and 27% respectively for corn ethanol co-product feed and that the US feed industry can accept animal feed from 69 billion l of corn ethanol production per year.

As noted above, the US feed market can only support 4–5 seaweed ethanol plants. Therefore, a single seaweed ethanol plant may need to market and distribute feed to a large geographical area to access a market that is large enough to take its total co-product output. Removing sodium from the feed, possibly with the aid of membrane separation systems, would reduce the minimum distribution area required and allow the feed market to sustain a larger number of ethanol plants.

6.2. Near-shore and off-shore farming potential

Globally, near shore farming could yield billions of liters of ethanol per year, but this is two orders of magnitude lower than global gasoline consumption. Therefore, open ocean seaweed farming will be required for seaweed ethanol to replace more than a small fraction of global gasoline use. As is the case for near shore farming in Northern China [10], fertilization may be needed for open ocean farming. Estimates of emissions from the production and application of fertiliser for seaweed farming are not available but, as is the case for core ethanol, these emissions are expected to be significant.

Total ethanol demand for BC (5% of 4.7 billion l [36]) could be met by farming 18% of the BC coastline at the same average rate (*i.e.* tonnes of seaweed per km of coastline) as China's current average rate. Conversion would require 1–2 average size commercial ethanol plants.

However, current farming costs in BC exceed the maximum feedstock cost in all modeled scenarios. Profitable production of seaweed ethanol will, therefore, require that farming costs are reduced. Current BC farming systems are for small scale, artisanal seaweed farming, and there is significant room for cost reduction [37].

6.3. Drying heat source

When using conventional (*i.e.* fossil fueled) drying equipment, seaweed ethanol has an EROI significantly less than one, and a CI significantly higher than current sources of ethanol. Therefore, drying with conventional equipment is likely not feasible. Only the use of renewable energy drying systems with high COP and powered by low CI electricity can produce seaweed ethanol with acceptable EROI and CI. Renewable heat resources (*e.g.* geothermal) may not be available near seaweed farming sites, and wet seaweed may need to be transported long distances to access renewable heat resources. The transport scenarios considered in the sensitivity analysis had minimal impact on CI and EROI, indicating that increased transportation distance does not significantly degrade ethanol EROI or CI.

For temperate coastal areas like BC, solar thermal drying may be problematic due to high rainfall and humidity. However in BC, seaweed is harvested during the summer months when rainfall is typically lower and solar resources are typically higher. Geothermal energy has been used for drying seaweed [38], and it can provide weather independent drying heat. BC has considerable geothermal resources [39] which are worthy of further exploration.

6.4. Seaweed composition

Seaweed composition variation, due to harvest season, farming location and farming year, has a significant influence on EROI. Of these, harvest season has the greatest effect, reducing EROI to less than 1.0 for seaweed harvested in March. This reduction is due to low fermentable content which results in higher co-product production per liter of ethanol and, thus, higher heat demand for

co-product production. Variation in farming location and farming year also reduce EROI through this same increase in heat demand.

6.5. Future processes

The case study examines a possible seaweed ethanol process similar to the dry grind corn ethanol process. However, a process similar to the wet grind corn process, that includes fractionation of the feedstock prior to fermentation, may be preferred. As the fermentation organisms in the Wargacki [14] seaweed conversion process are genetically engineered, it may be preferable to keep fermenting organisms separated from co-product streams. To address this concern, the fermentable components of seaweed could be extracted for ethanol production, and the unfermented components processed into animal feed or other co-products without any contact with modified organisms. Development of such a process may be straightforward as mannitol and some forms of laminarin are water soluble and commercial processes exist for the extraction of alginate [24].

7. Conclusion

A general well-to-wheel model of seaweed ethanol production was developed and applied to the case of ethanol produced from *S. latissima* farmed in BC, Canada. The general model includes a seaweed ethanol yield estimation tool that accounts for seaweed composition and its seasonal variations. The case study provides an analysis of large-scale seaweed ethanol production based on the dry grind ethanol process. This analysis includes the effects of energy input credits, GHG emission credits and revenue from animal feed as a co-product. The sensitivity of the results to variations in input parameters was also investigated. This investigation shows that, despite the challenges of high water content, high ash content and limited harvest season, seaweed ethanol is a promising biofuel with low CI, high EROI and potential for financially viability.

Animal feed produced as a seaweed co-product results in significantly improved CI. Without co-product credits, seaweed ethanol has a CI similar to that of sugarcane ethanol, but including co-product credits results in a significantly negative CI. Co-production of animal feed improves the financial viability of seaweed ethanol but the market for this feed may be limited by seaweed's naturally high sodium content.

Near shore seaweed farming has significant ethanol production potential, but offshore seaweed farming will be required for seaweed ethanol to significantly reduce global fossil fuel consumption. Seaweed ethanol could meet the current demand for ethanol in BC, but seaweed farming costs must be significantly reduced and solar thermal or geothermal seaweed drying must be proven feasible. Due to BC's short (*i.e.* 1–2 month) harvest season for *S. latissima*, seaweed drying is necessary to support ethanol production. Because the drying heat demand for seaweed is high, only renewable systems (*e.g.* solar thermal, geothermal) powered by low CI input electricity and with high COP are acceptable.

Seaweed composition varies significantly depending on chosen harvest season, farming location and farming year. As this variation can result in an EROI less than one, these factors must be considered for future seaweed ethanol projects.

This work shows that seaweed ethanol has promise as a low emission biofuel, even in regions that require seaweed drying and storage, and animal feed revenue may enable profitable production. The model developed here is based on three main assumptions: (1) large scale seaweed ethanol processing is similar in cost and energy use to dry grind corn ethanol processing, (2) seaweed ethanol co-product credits and co-product processing energy are similar to those for corn ethanol co-products and (3) co-product animal feed is equal in value to whole seaweed sold as animal feed. Further investigation of these key assumptions is needed to confirm the considerable promise of seaweed ethanol.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.06.010.

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